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Effects of Hurricane Andrew on Cypress (*Taxodium distichum* var. *nutans*) in South Florida

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ABSTRACT

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Cypress trees (*Taxodium distichum* var. *nutans* [Ait.] Sweet) of south Florida experienced little major damage or mortality as a result of Hurricane Andrew. In March, 1993, a survey was conducted to determine the relative magnitude and geographical distribution of damage to cypress as a result of the storm. Over 2000 trees in 16 cypress domes along a north-south transect roughly perpendicular to the direction of movement of the eye across the Florida peninsula were sampled for bark and branch damage. The force of hurricane winds is typically stronger on the right side of the eye, where the counterclockwise rotation of the storm intersects the forward track. The highest observed mortality per dome was 1.2% on the north side and 4% on the south side. Major damage (snapped trunks) occurred in only 4% of the trees surveyed, and seven months after the hurricane, most of these trees had produced basal or epicormic sprouts. Although major damage as a result of Hurricane Andrew was infrequent, minor damage to cypress was more common. In this study, 71% of the trees experienced branch damage, including loss of small branches, and 38% of the trees experienced bark damage. Damage, both major and minor, was related to the size of the tree. Both snapping and damage at all levels occurred less frequently in the smaller size classes than expected, if such damage occurred randomly with respect to tree size. The largest trees in south Florida occur in the center of domes, and these trees were more damaged than the trees on the perimeter of domes. For trees not snapped, bark damage and branch loss occurred most often in domes close to the eye; such damage decreased in severity and extent with increasing distance from the eye, and 26 km from the center of the eye only low levels of damage were recorded. Patterns of damage are asymmetrical around the eye. Levels of damage decreased with distance less rapidly on the north side of the eye than on the south side of the eye. Similar patterns of cypress damage have been noted after other hurricanes in this region, particularly Camille and Hugo. Cypress trees are likely to be affected by hurricanes multiple times in their life spans. Nonetheless, because of their wind resistance, cypress are expected to have only slight architectural changes over time due to wind-related events.

ADDITIONAL INDEX WORDS: *Everglades National Park, hurricane damage, wind damage.*

INTRODUCTION

Hurricanes, tornados, and other large-scale disturbances may affect the architecture of many forests (CURTIS, 1943; CRAIGHEAD and GILBERT, 1962; YIH *et al.*, 1991; WALKER *et al.*, 1992; OGDEN, 1992; FOSTER and BOOSE, 1992; and others). In the southeastern coastal region of the United States, return times of hurricanes average decades (SIMPSON and LAWRENCE, 1971; GENTRY, 1974; NEUMANN *et al.*, 1978). Several recent studies prior to Hurricane Andrew have suggested that it is likely that the characteristics of forests of the southeastern coastal plain of the United States have been shaped by repeated wind-related disturbances (PLATT and SHWARTZ, 1990; PUTZ and SHARITZ, 1991; GRESHAM *et al.*, 1991; SHARITZ *et al.*, 1992; PLATT and RATHBUN, 1995).

In this study, we describe the relative magnitude and geographical patterns of damage to pond cypress (*Taxodium distichum* var. *nutans* [Ait.] Sweet) in the path of Hurricane Andrew as it moved across the southern tip of the Florida peninsula. We recorded bark and branch damage, diameter, height, position in the dome, and distance from the center of the eye of the storm for over 2000 trees in sixteen separate domes. The damage estimates were used (1) to relate patterns of damage to the right (north) and left (south) of the eye, (2) to determine how this dam-

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age varied with distance from the eye, and (3) to compare damage to cypress in southern Florida with damage recorded in previous studies.

Damage assessments were made within and among domes. Trends in mortality and severe damage may suggest how hurricanes have had direct and immediate impact on population demography and architecture. Bark and branch damage estimates were taken to indicate both immediate and long-term impacts. It is probable that neither the bark nor the branch damage represented serious, long-term damage to the trees. These measurements of damage were useful, however, in describing how effects of the storm changed as distance from the eye increased.

Differential damage to the right and left sides of the eye was presumed to occur as a result of differences in wind direction and intensity. The strongest winds of a hurricane occur on the right side, where the counterclockwise rotation around the eye intersects the forward motion of the storm (SIMPSON and RIEHL, 1981; FOSTER and BOOSE, 1992). Measuring differences in impacts to the right and left side of the eye, as we have attempted in the present study, should help to refine general models predicting the geographical extent of hurricane damage to coastal forests.

STUDY AREA

Pond cypress (*Taxodium distichum* var. *nutans* [Ait.] Sweet) occurs throughout coastal regions of the southeastern United States, ranging from southern Delaware to south Florida and southeastern Louisiana (FOWELLS, 1965). In Florida, pond cypress is usually the dominant tree in domes. Domes are poorly drained to permanently wet depressions (MITSCH and GOSSELINK, 1986), roughly circular in shape, with the deepest water overlying a peat layer in the center. In general, smaller trees are located at the perimeter, and larger trees (diameter and height) are located in the interior of the domes (MITSCH and GOSSELINK, 1986). The characteristic dome shape may be due to the greater frequency of fire around the edges of the dome, where the soil is dry for most of the year (EWEL and MITSCH, 1978). These fires can kill young trees before they become fire-resistant, thus preventing these trees from obtaining sizes similar to those in the interior (DUEVER *et al.*, 1984).

Most domes in extreme southern Florida are small, ranging from <1 to 15-20 ha (EWEL, 1990). They occur in nutrient poor (EWEL, 1991; BROWN, 1984), shallow depressions in the limestone bedrock (DUEVER *et al.*, 1984). The limestone bedrock is highly dissected, with many cracks and crevices, and the peat layer is not as well developed as in the domes of northern Florida.

The cypress domes used in the current study are located in the Big Cypress National Preserve, Monroe County, and the Everglades National Park, Dade County, Florida. The nature of the domes has been described by several authors (EWEL and MITSCH, 1978; DUEVER *et al.*, 1984; EWEL, 1990; and others). The domes of Big Cypress National Preserve (BCNP) were imbedded in wet prairies or in Slash Pine (*Pinus elliottii* var. *densa*) savannas. In Everglades National Park (ENP), the cypress domes studied were imbedded in wet prairie or in cypress prairie composed of small (<15 cm diameter and <3 m in height), isolated cypress (DUEVER *et al.*, 1984).

Hurricane Andrew

On August 24, 1992, Hurricane Andrew moved almost due west at a heading of 275 degrees across the tip of the Florida peninsula, with sustained wind speeds of 232 km/h (RAPPAPORT, 1993). Wind gusts were at least 280 km/h (RAPPAPORT, 1993) and perhaps as much as 340 km/h (ARMENTANO *et al.*, 1995). This was a strong storm (WAKIMOTO and BLACK, 1994), but remained relatively compact, with an eye diameter of only 24 km (STONE *et al.*, 1993). The width of the band of defoliated vegetation along the path across Florida was narrow, approximately 50 km (PIMM *et al.*, 1994). STONE *et al.* (1993) estimated the asymmetric wind bands to extend outward from the eye about 48 km to the southeast, southwest and northwest, and about 113 km to the northeast (right side of eye, leading edge). Initial surveys conducted shortly after the hurricane indicated that the most severe damage occurred in areas within or near the eyewalls of the storm (OGDEN, 1992; LOOPE *et al.*, 1994).

The track of the storm across south Florida is illustrated in Figure 1. Locations of the inner and outer eyewall were made from composite radar images (every 15 minutes) during the passage of Andrew along the 50-100 km wide path across the Florida peninsula. Details of the methods used in mapping the storm track are pro-

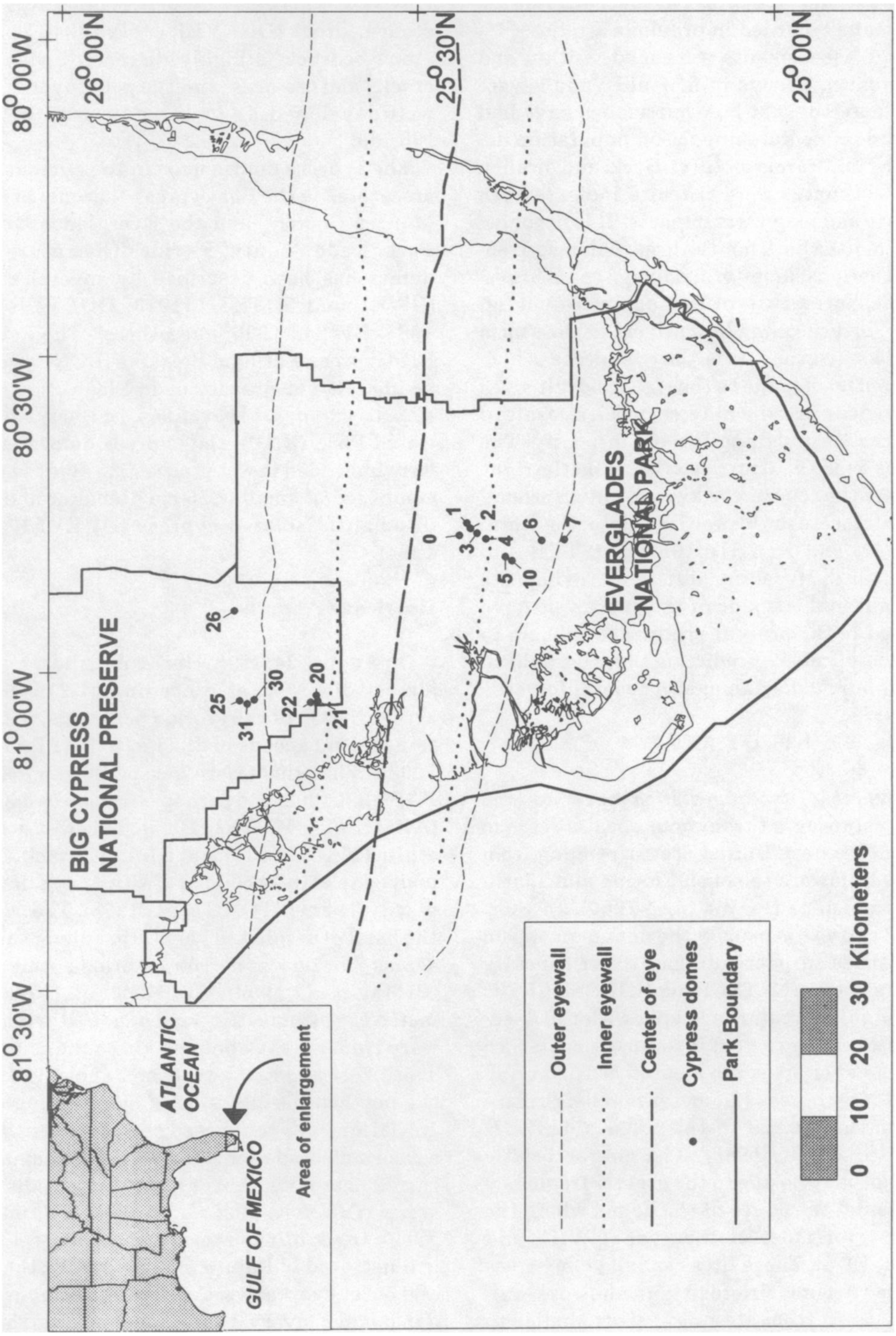

Figure 1. Map of south Florida, showing the path of Hurricane Andrew in relation to the locations of cypress domes studied in Everglades National Park and Big Cypress National Preserve. Numbers indicate domes in Table 1.

Table 1. *Characteristics of cypress domes sampled in South Florida.*

Dome Number	Distance from Center of Eye (km)	Size (m^2)	Number of Trees	Mean dbh (cm ± s.e.)	Mean Height (m ± s.e.)[a]	Number of Snapped Trees	Mortality (%)
20	11.7 N	133	78	3.50 ± 0.28	2.69 ± 0.11	0	0.00
21	11.4 N	154	47	3.45 ± 0.28	2.50 ± 0.00	0	0.00
22	12.3 N	380	80	8.30 ± 0.44	5.56 ± 0.34	3	1.25
30	22.0 N	174	59	5.24 ± 0.61	4.11 ± 0.33	1	0.00
31	23.0 N	177	57	6.61 ± 0.44	3.64 ± 0.28	0	0.00
25	24.0 N	255	244	5.83 ± 0.20	3.87 ± 0.16	2	0.00
26	26.0 N	597	166	3.79 ± 0.25	2.71 ± 0.08	0	0.00
0	7.6 S	177	50	6.56 ± 0.86	3.80 ± 0.31	4	4.00
1	8.4 S	707	117	6.15 ± 0.37	3.65 ± 0.19	14	[b]
2	9.1 S	836	280	5.66 ± 0.21	3.62 ± 0.13	20	0.71
3	9.5 S	1292	319	7.03 ± 0.24	4.47 ± 0.14	28	0.00
4	11.5 S	707	208	5.36 ± 0.22	3.32 ± 0.13	3	0.00
5	15.8 S	511	224	6.25 ± 0.28	4.38 ± 0.19	3	0.45
10	16.1 S	143	77	6.79 ± 0.42	3.41 ± 0.22	0	0.00
6	20.4 S	165	70	5.53 ± 0.40	3.07 ± 0.19	1	1.43
7	24.0 S	85	77	3.81 ± 0.31	2.98 ± 0.15	0	1.30

[a]Mean height was estimated based on the midpoint of the class values described in text.
[b]The mortality for this dome was not calculated due to a field recording error.

vided in ARMENTANO *et al.* (1995). This track crossed areas of Everglades National Park and Big Cypress National Preserve containing cypress domes.

METHODS

Field Data Collection Methods

In March, 1993, seven months after the hurricane, we studied 16 cypress domes directly impacted by the storm in the Everglades National Park (ENP) and Big Cypress National Preserve (BCNP). We selected cypress domes based on size and accessibility by road or swamp buggy (modified 4 × 4 vehicle) along a transect located through the path of the hurricane eye and extending in a north-south direction, roughly perpendicular to the direction of movement (Figure 1). A total of 2153 trees were sampled in 16 domes. Characteristics of domes are presented in Table 1. In the north, the seven domes sampled ranged irregularly from 11 to 26 km from the center of the eye. Domes 20, 21, and 22 were located southeast of the Lostmans Pines region, and domes 25, 30, and 31 were located due north of the Gum Slough region (see ARMENTANO *et al.*, 1995 and PIMM *et al.*, 1994, for details of these areas). The nine domes in the south, located west of Long Pine Key, were sampled at more regular intervals, from those located inside the eye to those located up to 24 km away from the center of the eye (Figure 1). Cypress domes within the eyewalls of Hurricane Andrew, both north and south of the eye, probably experienced sustained wind speeds >200 km/h (ARMENTANO *et al.*, 1995).

Each dome was located on a topographic map (USGS map number 25080-A1-TB-250), and the distance from the center of the eye was measured. The diameter of each dome was measured in the field. Small domes (85 m^2 to 1292 m^2) were selected so that all trees could be censused quickly. The domes to the north ranged in size from 133 m^2 to 597 m^2, with 47 to 244 trees per dome. The domes in the south ranged from 85 m^2 to 1292 m^2, with 50 to 319 trees per dome (Table 1). Within each dome, trees located in the outer one-third of the radius of the dome were classified as perimeter trees. Those located in the inner two-thirds of the radius were classified as interior trees. Perimeter or interior classification provided an estimate of how protected the trees are from winds. In each dome, sizes were measured for all trees ≥1 cm in diameter. Each tree was placed in one of three height classes: 1.5–5 meters (m) tall, 5–10 m, and greater than 10 m. Diameter at breast height (hereafter, dbh), 1.5 meters above the ground, was recorded for all trees. Similar ranges of sizes of trees were present in domes on both the north and south sides of the hurricane track.

The mean diameter of trees in domes on the north side ranged from 3.5 ± 0.3 to 8.3 ± 0.4 cm (± standard error) and, on the south side, ranged from 3.8 ± 0.3 to 7.0 ± 0.2 cm (Table 1). In the domes studied, most perimeter trees were 1–10 cm diameter, and the interior trees were 10–30 cm; although, there were some small diameter trees in the interior portions of the domes.

All snapped trees were recorded as dead or alive, indicated by growth of epicormic shoots at the base or along the trunk. To estimate mortality in each dome, each tree was classified as alive, dead, or unknown. The unknown category included trees that flushed needles following the hurricane (*i.e.*, in the fall of 1992), but had no green needles present at the time of the survey. Trees that had not flushed needles after the hurricane and had no green needles at the time of the survey were considered dead. About half of the dead trees were snapped, with no basal or epicormic sprouts.

We examined wind related damage of both bark and branches. The damage was placed into numerical scales that represented increasing intensity of damage. Damage to the bark was recorded using the following criteria: (1) peeling or abraded outer bark, (2) damage that exposed the cambium layer, with the area involved not exceeding about 15 cm in length or 4 cm in width, and (3) more extensive exposure or damage of the cambium. Category 3 bark damage did not include torn bark resulting from a snapped trunk. Using a similar three category scale, branch damage was classified as (1) smallest branches broken or missing, (2) larger outer branches broken or missing, and (3) large branches (>3 cm diameter) broken off at the trunk.

Data Analyses

The percentage of trees in the population in each of several size classes was calculated, excluding dead trees. The size classes were based on five cm intervals in dbh (0–4.9 cm, 5.0–9.9 cm, 10–14.9 cm, *etc.*). The percentage of trees snapped in each size class was compared to the overall distribution of trees in the population. Similar tests were performed to examine the relationship between dbh and damage. The damage categories were created by summing all of the trees in each size class over all levels of damage (*e.g.*, Level 1, 2, and 3).

Logistic regression was used to predict levels of bark and branch damage, using distance from the center of the eye, north/south identifiers, dbh, height, and position in dome (interior or perimeter) as predictive variables; the Wald chi-square test was used to identify relationships (HOSMER and LEMESHOW, 1989). For this analysis, values for height were the approximate midpoints of each size class (class 1 = 2.5 m, class 2 = 7.5 m, and class 3 = 12.5 m).

The logistic regressions were carried out in the SAS statistical package (SAS INSTITUTE, 1988). For all significance tests, alpha values were held at 0.05.

RESULTS

Mortality and Snapping

Summary characteristics were compiled for each dome (Table 1). Relatively little major damage (snapped trees or mortality) occurred in the cypress domes sampled. The highest observed mortality per dome was 1.2% on the north side, at a distance of 12.3 km from the center of the eye, and 4% on the south side, at a distance of 7.6 km from the center of the eye. The domes on the north side of the eye had fewer snapped trees (0.8% of total trees on the north side), with a maximum of three in any single dome. The domes on the south side of the eye experienced more snapped trees (5% of total trees on the south side). The majority of snapped trees occurred in only three domes and were located inside the eye. Of the 2153 trees sampled, only 79 were snapped and only 17 trees were considered dead. About half of the 17 dead trees had been snapped.

Bark and Branch Damage

The logistic regression model in which distance from the center of the eye, north/south categories, dbh, height, and position in the dome are used as predictors of all levels of bark and branch damage assumes that the three levels of damage are parallel lines and fits the predictors as a proportional odds model. However, the chi-square values (bark $\chi^2_{df=10} = 73.71$, $p = 0.0001$, and branch $\chi^2_{df=10} = 137.44$, $p = 0.0001$) indicated that a proportional odds model was inappropriate for these data. As a result, logistic regression was then run on a data set that tested for differences in only two levels of damage, using a reduced model. For both bark and branch, separate comparisons were made between level 0 (no measurable damage) and each level of measurable damage: Level 1 (light damage), Level 2 (moderate damage), and Level 3 (heavy damage).

Results are summarized in Tables 2 and 3. The Wald chi-square value was used to determine significant contributions. Each of the predictor variables is assumed to remain constant, as other variables are changed. For the comparisons 0:1 and 0:2, the variables of distance, north/south, dbh, and position are significantly related to the outcome of damage. For the comparison 0:3, position is not included in the predictors. Height of tree was not included as a significant predictor of damage in any of the comparisons.

The Pearson correlation analysis indicated that height and dbh were strongly related ($R = 0.67$). Therefore, the same logistic models were run, without dbh as a predictor variable. In these models, height was a significant predictor of damage, although dbh was a better predictor for this analysis.

Factors Controlling Damage

In the logistic regressions (reduced models), the standardized estimate value was used to determine the relative contribution of each predictor variable. In general, positive values for standardized estimate values indicate an inverse relationship between damage and each predictor variable, and negative values indicate a direct relationship. The comparisons were for bark and branch at no damage and each level of damage (0:1, 0:2, 0:3). At all levels of damage, distance from the center of the eye was an important predictor. For bark damage, the comparison of no damage to light damage (0:1) gave a standardized estimate of 0.61 and increased with increasing level of damage to 1.26 for heavy damage (0:3). For branch damage, the standardized estimate ranged from 0.52 (0:1) to 1.06 (0:3). The positive values indicate that greater damage occurs at lower values of distance, or that damage was greatest nearest the eye.

The relationship between levels of damage and location north or south of the eye was also positive. The standardized estimate for bark damage

Table 2. *Bark damage predicted from logistic regressions used reduced models for comparisons between no damage and each level of measurable damage.*

Variable	DF	Parameter Estimate	Standard Error	Wald Chi-Square	Pr > Chi-Square	Standardized Estimate
		A. Bark Damage, level 0 compared to level 1 (light damage)				
Intercept	1	−0.1325	0.2888	0.2107	0.6463	
Distance	1	0.1741	0.0140	154.8597	0.0001	0.612662
North/south	1	0.8629	0.1653	27.2605	0.0001	0.228303
dbh	1	−0.3632	0.0252	207.0058	0.0001	−0.721504
Height	1	0.0337	0.0333	1.0259	0.3111	0.040110
Position	1	−0.4157	0.1233	11.3589	0.0008	−0.114107
		B. Bark Damage, level 0 compared to level 2 (moderate damage)				
Intercept	1	−0.4657	0.5254	0.7857	0.3754	
Distance	1	0.2922	0.0318	84.2230	0.0001	1.048827
North/south	1	1.2152	0.3017	16.2220	0.0001	0.325445
dbh	1	−0.3953	0.0423	87.2808	0.0001	−0.689361
Height	1	0.0507	0.0612	0.6853	0.4078	0.051415
Position	1	0.1350	0.2192	0.3719	0.5381	0.037222
		C. Bark Damage, level 0 compared to level 3 (heavy damage)				
Intercept	1	0.6820	0.7547	0.8166	0.3662	
Distance	1	0.3505	0.0486	52.0560	0.0001	1.255913
North/south	1	1.1900	0.4210	7.9894	0.0047	0.318508
dbh	1	−0.4350	0.0545	63.6736	0.0001	−0.790648
Height	1	−0.0535	0.0747	0.5122	0.4742	−0.056324
Position	1	−0.5000	0.3126	2.5585	0.1097	−0.137785

Table 3. *Branch damage predicted from logistic regressions using reduced models for comparisons between no damage and each level of measurable damage.*

Variable	DF	Parameter Estimate	Standard Error	Wald Chi-Square	Pr > Chi-Square	Standardized Estimate
		A. Branch Damage, level 0 compared to level 1 (light damage)				
Intercept	1	−2.3724	0.3442	47.4992	0.0001	
Distance	1	0.1447	0.0138	110.6126	0.0001	0.518857
North/south	1	2.1155	0.1925	120.7214	0.0001	0.557707
dbh	1	−0.3784	0.0301	158.2283	0.0001	−0.691933
Height	1	0.0350	0.0511	0.4701	0.4929	0.035939
Position	1	−0.6089	0.1208	25.4010	0.0001	−0.167895
		B. Branch Damage, level 0 compared to level 2 (moderate damage)				
Intercept	1	−2.1453	0.5038	18.1305	0.0001	
Distance	1	0.3111	0.0259	144.3358	0.0001	1.058004
North/south	1	2.8089	0.3181	77.9666	0.0001	0.684792
dbh	1	−0.6109	0.0476	164.8805	0.0001	−1.309026
Height	1	−0.0616	0.0610	1.0196	0.3126	−0.075776
Position	1	−1.3428	0.2007	44.7642	0.0001	−0.369050
		C. Branch Damage, level 0 compared to level 3 (heavy damage)				
Intercept	1	−0.3469	0.8956	0.1501	0.6985	
Distance	1	0.2928	0.0485	36.3735	0.0001	1.020384
North/south	1	5.0374	0.6803	54.8258	0.0001	1.316670
dbh	1	−0.7168	0.1026	48.7719	0.0001	−1.383310
Height	1	0.0515	0.1296	0.1578	0.6912	0.049839
Position	1	−1.0038	0.4621	4.7196	0.0298	−0.274739

ranged from 0.23 (0:1) to 0.32 (0:2, and 0:3); for branch damage, the estimates ranged from 0.56 (0:1) to 1.32 (0:3). In the data set, north and south were binomial characters, and the north was coded as zero, the south as one. Therefore, the positive values indicate that more damage occurred to the south of the eye. This presumably reflected the location of some domes inside the south eyewall; these domes were the ones that sustained the greatest damage and mortality.

The relationship between position in the dome and the levels of damage was less clear. Position was also treated as a binomial character, with interior positions coded as one and perimeter as zero. The standardized estimates for bark damage ranged from −0.11 (0:1) to 0.04 (0:2), and −0.14 (0:3); branch damage was negative throughout and ranged from −0.17 (0:1) to −0.37 (0:2). The negative values indicate that location in the interior of the dome predicted more damage in the model.

The relationship between dbh (size) and levels of damage, however, is negative. The standardized estimates for bark damage ranged from −0.69 (0:2) to −0.79 (0:3); branch damage ranged from −0.69 (0:1) to −1.38 (0:3) These negative values indicate that greater damage is predicted at larger values of dbh.

Because size was an important predictor of damage, further non-parametric comparisons were made (SOKAL and ROHLF, 1981). The trees were separated into 5 cm size classes (*e.g.*, 1–4.9, 5–9.9, 10–14.9, *etc.*). Percentages of trees in each size class and of snapped trees in each size class are presented in Figure 2. Almost half (47.4%) of the trees in the sampled population occurred in the smallest size class (1–5 cm), and progressively smaller percentages occurred in the larger size classes. In contrast, trees below 5 cm dbh were snapped less often than expected if snapping had occurred randomly with respect to tree size (Kolmogorov-Smirnov nonparametric test for differences between two distributions was not significant $D = 0.431 \gg D_{0.05} = 0.166$).

The percentages of bark and branch damage (not including snapped trees) were compared to the percentage of trees in each size class. Both bark and branch damage comparisons revealed that the trees in the smallest size classes (1–5 and 5–10 cm) were less damaged than expected on the

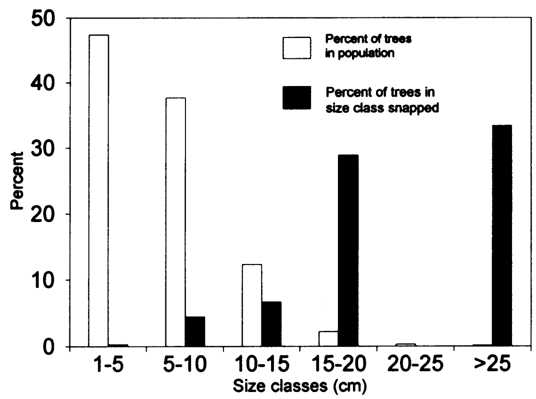

Figure 2. Percent of sampled trees in each size class in south Florida cypress domes (open bars), and percent of trees in each size class that were snapped (solid bars).

basis of the size distributions of individuals in the population (Kolmogorov-Smirnov nonparametric test for differences between two distributions was not significant: Bark $D = 0.293 \gg D_{0.05} = 0.0575$; Branch $D = 0.127 \gg D_{0.05} = 0.046$).

DISCUSSION

Our study of cypress in south Florida indicated that this species is very resistant to hurricane damage. Few trees (4% of all trees sampled) were snapped by Hurricane Andrew, and only 12% of snapped trees died. In addition, only eight trees were dead that had not been snapped. The low mortality observed in this study suggests that hurricanes do not play a major short-term role in the population dynamics of cypress in small domes in south Florida. Patterns may differ for larger domes. Field observations of one large dome located near the eye (between sites 0 and 2) contained over 50 large cypress trees that had been tipped up or snapped by the hurricane. This damage level was far higher than that observed in any of the smaller domes.

The general levels of mortality and severe damage (snapped trunks or tipped up trees) observed in our study were consistent with data from other studies. All have reported that cypress are very resistant, noting low levels of severe damage and mortality rates <4% (see CRAIGHEAD and GILBERT, 1962; TOULIATOS and ROTH, 1971; DUEVER *et al.*, 1984; GRESHAM *et al.*, 1991; LOOPE *et al.*, 1994). PUTZ and SHARITZ (1991) estimated that about 19% of the dominant trees (cypress and water tupelo, *Nyssa aquatica*) in forested sloughs and bottomlands of South Carolina affected by Hurricane Hugo suffered serious damage (>25% crown lost). Uprooting of cypress and tupelo was uncommon compared to bottomland forest species in the sloughs. Mortality in the sloughs was low (<1% for the cypress and tupelo), and almost all of the mortality resulted from snapped trunks (SHARITZ *et al.*, 1992). In contrast, bottomland forests dominated by Sweetgum (*Liquidambar styraciflua*), American Elm (*Ulmus americana*), Ash (*Fraxinus* sp.), and Oaks (*Quercus* sp.) suffered much more serious damage. About half of the bottomland forest trees were uprooted, snapped, or had lost a substantial number of large branches.

All studies also have noted that tipped-up cypress are uncommon, with mortality primarily occurring when trunks are snapped. In south Florida, cypress tend to be strongly rooted in the limestone substrate. In areas where organic sediments are present in the depression, the trees tend to be less strongly anchored and may be more susceptible to tipping up (DAVIS *et al.*, 1992). TOULIATOS and ROTH (1971) suggest several factors that increase the wind resistance of a tree, including strength of wood, shape of crown, extent and depth of root system, and shape of the trunk. Cypress have deep, well established lateral and tap roots and a buttressed trunk. These, combined with an open crown, make cypress one of the more resistant species to major wind damage.

Other forest types are generally affected more severely than cypress forests. FOSTER and BOOSE (1992) reported on forest types impacted by the 1938 New England hurricane; some forest types dominated by mixed pine and hardwoods experienced severe damage (>60%), including canopy trees that were uprooted, snapped off or leaning in such a way that recovery was unlikely. SLATER *et al.* (1995) reported that in hardwood hammocks affected by Hurricane Andrew, 85% of all trees suffered major damage, and that 11.5% of all stems >2 cm dbh were killed. BALDWIN *et al.* (1995) reported that in mangrove forests impacted by Hurricane Andrew, mortality ranged from 60 to 85%, depending on species. Similar results were obtained by SMITH *et al.* (1994).

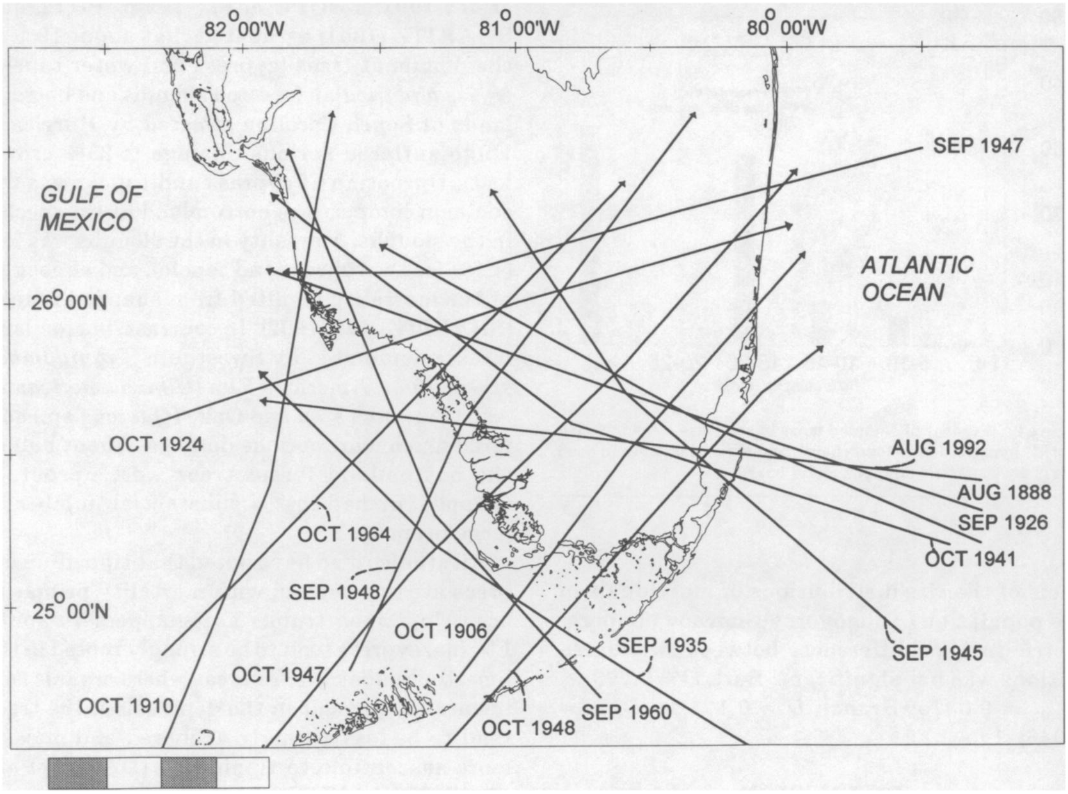

Figure 3. Tracks of 15 major hurricanes with wind speeds >120 km/h across south Florida over the past 100 years, labeled by date (after Neumann *et al.*, 1992).

Although major damage as a result of Hurricane Andrew was infrequent, minor damage to cypress was common. In this study, 71% of cypress trees experienced branch damage. Most other studies also indicated that the damage to cypress from hurricanes was primarily defoliation and loss of small branches (TOULIATOS and ROTH, 1971; DUEVER *et al.*, 1984; PUTZ and SHARITZ, 1991). GRESHAM *et al.* (1991) studied Hurricane Hugo, suggesting levels of damage which are similar to those resulting from Hurricane Andrew. Their data indicate that up to 72% of cypress trees showed only minor damage. Nonetheless, 38% of the cypress trees in our study experienced bark damage. The bending and twisting of a tree during the hurricane resulted in the bark being abraded or torn. Such bark damage, along with major branch breakage and loss has been noted in other studies, which have suggested that bark damage may leave trees more susceptible to insect or fungal infestation or other disease (CRAIGHEAD and GILBERT, 1962; PUTZ and SHARITZ, 1991; SHARITZ *et al.*, 1992). Damage, both minor and major, was related to size of the tree in our study. Levels of damage increased with size of tree. Both snapping and damage at all levels occurred less frequently in the smaller size classes than expected based on chance damage of trees. The smaller trees are more flexible and may bend and twist during a storm with only small effect. GRESHAM *et al.* (1991) indicated that the larger sized cypress were heavily damaged, while smaller trees were either not damaged or only lightly damaged by Hurricane Hugo. CRAIGHEAD and GILBERT (1962) studied the effects of Hurricane Donna that crossed the tip of Florida in 1960. They concluded that damage to cypress in the Everglades National Park occurred mostly in the more mature cypress domes and sloughs. BROKAW and WALKER (1991), in their summary of effects of Caribbean hurricanes, also indicated that in several forest types, the tallest trees with the largest dbh were those most likely to be damaged by hurricanes.

Similar patterns have been noted for other species. CURTIS (1943) studied forests of the New England area and demonstrated that crown shape, crown size, height, and diameter of a tree were factors that influenced the extent of damage during a wind-storm. The larger the diameter and the taller the tree, the greater the wind force required to fell the tree. In trees with a small crown (10–20% of the height of the tree) or open architecture crown, CURTIS (1943) suggested that the resistance was not sufficient to uproot the tree or break the stem.

Size of tree was more important than location in a dome in predicting damage. Nonetheless position is still important. We expected interior trees to be more protected from the winds than trees on the perimeter of the dome. However, analyses indicated that trees in the interior of domes received higher levels of damage. This probably reflects the larger size and height of trees in the center of the dome, rather than protection from the outer trees. CRAIGHEAD and GILBERT (1962) also noted that a few of the taller cypress in the center of domes and sloughs were toppled.

Bark damage and branch loss and mortality occurred most often in domes close to the eye; such damage decreased in severity and extent with increasing distance from the eye. Although patterns of bark and branch damage from Hurricanes Andrew and Hugo were similar, only minor damage was noted 26 km from the center of the eye of Hurricane Andrew. This was different than in Hurricane Hugo, which damaged trees up to 91 km from the eye (GRESHAM *et al.*, 1991). Hurricane Andrew was a much more compact storm than Hurricane Hugo, although the sustained wind speeds were similar. Hence, size of storm may affect the extent of area in which damage occurs, as well as the rate at which measurable damage decreases with increasing distance from the eye.

The impact of hurricanes is asymmetrical around the eye. Levels of damage decreased with increasing distance from the center of the eye. The damage to cypress decreased less rapidly to the north than to the south. Thus, results of our study are consistent with those from the few other studies that compare damage to the right and left of the eyewall. SMITH *et al.* (1994) report that in mangrove forests impacted by Hurricane Andrew, damage to the north decreased less rapidly with increasing distance to the north than to the south of the eye. A pattern of increased damage to trees on the right side of the eye was observed in Alabama and Mississippi following Hurricane Camille (TOULIATOS and ROTH, 1971). FOSTER and BOOSE (1992) suggest that in New England forests studied more damage was sustained to the right than the left side of the eye. As Hurricane Andrew approached the Louisiana coast after crossing the Florida peninsula, STONE *et al.* (1993) report that the storm surge to the east (right) was higher than the surge to the west (left) of the eye.

Cypress trees are likely to be affected by hurricanes multiple times during their life spans (PURVIS, 1973; GRESHAM *et al.*, 1991). As indicated in Figure 3, some regions of south Florida have experienced at least as many as fifteen hurricanes with wind speeds greater than 120 km/h within the past century (SIMPSON and LAWRENCE, 1971; GENTRY, 1974; NEUMANN *et al.*, 1993).

Repeated minor damage to cypress can affect the tree architecture. Generally, if branches are lost in a hurricane, the tree will continue to grow via secondary branches and epicormic sprouts. In hurricane impacted regions, repeated branch loss in cypress typically results in a flat-topped structure of trees. Because cypress may be impacted by wind-related disturbances several times during their life spans, trees weakened in one storm may be more susceptible to damage in another storm (PUTZ and SHARITZ, 1991).

This flat-topped structure of cypress is an architecture different from that observed in hurricane impacted hardwood forests. In tropical hardwood hammocks, resprouting from the main stem or base is the primary form of recovery after hurricane damage (SLATER *et al.*, 1995). This resprouting allows trees to reoccupy the canopy in much the same architectural shape as prior to the storm. FOSTER (1988) reports that in New England hardwood forests, recovery is usually from resprouting or seed with the trees rapidly occupying a canopy position. In mangrove communities, advance recruits are the primary means of recovery of red mangroves, while white and black mangroves resprout from the trunk, base or roots (BALDWIN *et al.*, 1995). Because the damage to these communities tends to be more severe, none of these communities attains flat-topped tree architecture observed in cypress communities. We predict that such tree architecture will remain for some time as the only visible legacy of Hurricane Andrew in south Florida cypress domes.

CONCLUSIONS

The results of this study indicated that cypress was very resistant to hurricane damage. The highest observed mortality in any dome was 4%. Cypress trees did not readily tip-up and mortality was primarily caused by the trunk snapping. While cypress were not severely damaged by Hurricane Andrew, some damage was sustained. In this study, 71% of cypress trees experienced branch damage and 38% of trees sustained bark damage. Both major and minor damage were strongly related to size of the tree. Larger trees sustained more damage, including severe damage, than smaller sized trees. The largest trees in south Florida tended to occur in the center of cypress domes, where the highest levels of damage were observed. The geographical patterns to damage were related to the distance from the center of the eye and asymmetrical patterns of damage to the right and left of the eye of the storm. Levels of both severe and minor damage decreased with increasing distance from the center of the eye; levels of damage decreased less rapidly to the right side of the eye than to the left side of the eye. Because levels of severe damage to cypress were low compared to other forested communities of south Florida impacted by Hurricane Andrew, the cypress trees would be expected to only show slight architectural changes over time due to wind-related events.

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RESUMEN

Los cipreses (*Taxodium distichum* var. *nutans* [Ait.] Sweet) del sur de Florida presentaron baja frecuencia de daño grave y baja mortalidad por efecto del huracán Andrés. En marzo de 1993 se condujo un relevamiento para determinar la magnitud y distribución geográfica del daño causado a los cipreses por esta tormenta. Se evaluó el daño en más de 2000 cipreses distribuídos en 16 bosquetes a lo largo de una transección norte-sur, perpendicular a la dirección de avance del huracán. Los vientos de máxima intensidad ocurren la derecha del ojo del huracán, donde el sentido antihorario de rotación de la tormenta se intersecta con su dirección de avance. Las mortalidades máximas observadas por bosquete fueron de 1.2% en la parte norte de la transección y de 4% en la parte sur. Solamente 4% de los árboles estudiados presentaban el tronco partido, y la mayor parte de ellos había rebrotado desde la base o desde el tronco 7 meses después del meteoro. Si bien la frecuencia de daño grave fue baja los daños menores fueron frecuentes. Entre los árboles observados en este estudio, 71% presentó lesiones en las ramas, incluyendo pérdida de ramas pequeñas, y 38% presentó abrasión de la corteza. Tanto el daño grave como el daño menor estuvieron

asociados con el tamaño de los árboles. Entre los árboles pequeños las frecuencias de daño en general y de partido del tonco fueron menores que las esperadas si su probabilidad fuese independiente del tamaño. Los cipreses más grandes, que están en el centro de los bosquetes, fueron menos dañados que los menores, ubicados en la perisferia. Entre los árboles que no resultaron partidos, la frecuencia e intensidad de lesiones en la corteza disminuyó a mayor distancia del ojo del huracán, y alcanzó valores muy bajos a 26 km del mismo. La intensidad del daño disminuyó más abruptamente hacia el sur que hacia el norte del mismo. Los efectos del huracán Andrés sobre los cipreses son similares a los observados luego de otros huracanes, como Camila y Hugo, que también afectaron el sur de Florida. Los cipreses resultarían afectados por huracanes varias veces a lo largo de su vida. Sin embargo, debido a su resistencia al viento, estos árboles sólo experimentarían ligeros cambios de forma debidos al efecto de los huracanes a través del tiempo.